UNDERGROUND CONSTRUCTION, GEOLOGY AND GEOTECHNICAL RISK

Dr. Priscilla P. Nelson
Department of Mining Engineering
Colorado School of Mines

ABSTRACT

Population increase means more mega-cities, growing very fast as “compact cities” for which surface space becomes a priority. This creates a particular urgency to make the underground space of the future cheaper to construct, and more reliable in construction and operational performance. The cost and performance of underground projects is intimately linked to the understanding and management of geologic risk for both construction and life-cycle performance of subsurface facilities. This includes not only expected and unexpected uncertainties, but also the anticipation that urban growth will extend into increasingly fragile and poor quality geotechnical environments, and that the projects will involve larger and deeper openings.

This paper assesses the state-of-practice and future possibilities for improved management of geologic risk, including risk avoidance, new materials and methods, ground improvement, life cycle engineering for sustainability, and better subsurface characterization. Some geologic risks have plagued for centuries, e.g., ground water, shallow cover and weathered rock, subsidence and impact on structures, stresses and stress relief, progressive deterioration. New risks have arisen associated with new technologies, unexpected stress-driven ground behavior at increased depth, design for higher water inflows and pressures, and the requirement for larger spans and a variety of excavated shapes. In addition, a better understanding of the spatial variability of soil and rock structure is needed a priori, including application of geophysical and remote sensing techniques. Our site investigations of the future need to be increasingly confirmatory rather than exploratory, and we should plan more effectively for ground improvement before construction.

INTRODUCTION

Sustainable urban underground development must meet current human needs while conserving spatial resources and the natural and built environments for future generations to meet their needs. This requires a systems perspective for integrated above and below ground resource use and management, and must include consideration of cost effectiveness, longevity, functionality, safety, aesthetics and quality of life, upgradeability and adaptability, and minimization of negative impacts while maximizing environmental benefits, resilience, and reliability (Bobylev, 2009).

Population and urban growth will continue, but not always in predictable ways. In the past, we have lived through urban migration and expansion, followed by suburbanization, and now perhaps the concept of the compact city describes how our cities will change in the future. The compact city concept is intimately wedded to increasing and intensively planned use of underground space and engineers, architects and planners have challenges in preparing our old and new infrastructure for the future.

The underground construction industry has consistently provided the world with needed infrastructure, meeting schedule and scope goals. While it is generally appreciated that the nation must invest in the rehabilitation of existing infrastructure, there continues to be a lack of political and public will to do so. These are effectively cyberphysical infrastructure systems that have not been maintained, causing unexpected vulnerabilities and cascading failures (ASCE, 2017; AWWA, 2001). As urban infrastructure systems become increasingly unreliable in one city, an interesting market impact arises - it is likely that more of the world's leading industries will relocate headquarters to other cities and countries with more reliable infrastructure.

Significant impacts from extreme events (including climate change, earthquakes, tsunamis, floods, storms) are arguably becoming more frequent and costly (see Figure 1). Our future global cities must support the population both through disasters and for daily living, perhaps analogous to the human body's resistance and resilience to a high-grade fever and also to manage a low-grade infection (Nelson, 2016). The resilience of our urban communities depends on many factors that extend beyond the physical system complexities and interdependencies (Nelson and Düzgün, 2018). Therefore, social network research is needed to provide linked and registered metrics through crowd sourcing for event impacts, yielding change trajectories over time (Anex et al., 2006;

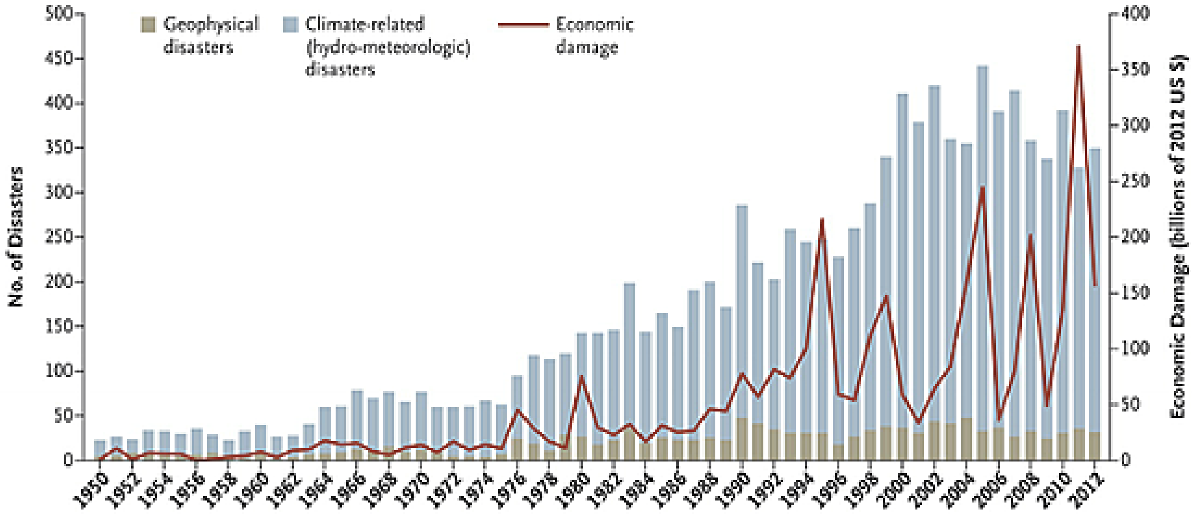

Figure 1. Recent History of Disasters and Impacts.
http://www.accuweather.com/en/weather-blogs/climatechange/steady-increase-in-climate-rel/19974069

Bobylev, 2009 and 2016). Social networks, crowd sourcing, IoT (Internet-of-Things) through location-based services potentially allow those responsible for infrastructure to access social data about impacts quickly, and software can be used to capture and analyze the public's acute reactions to extreme events (Sherrieb et al., 2010) in real time, providing an opportunity to respond and maximize the social and infrastructure performance resilience.

State-of-practice design and operation of infrastructure systems from the past has led to robust-enough systems for which we have sufficient experience to permit simplifying assumptions that enabled operation with minimal monitoring. For many systems, there were sufficient reserves for acceptable service under known stress. However, as we interconnect aging systems into larger networks and observe decreasing performance levels, reductions in excess capacity and new stresses (e.g., poorly understood interdependencies, attack), we learn that our systems have lost robustness. As our system complexity has increased, many of the design simplifications are no longer acceptable, and new concepts of design and control provide an opportunity for new approaches to system management.

In many cases, the design loads used by engineers at the time of construction of our older infrastructure, may not be the loads we would use now. Our design and professional codes have always incorporated factors of safety against failure by such events, but the impacts of recent events have been more severe and complex with interdependent responses. Engineering professionals, construction contractors, and urban planners and managers must work together to identify new ways to retrofit and bolster our infrastructure against extreme event impacts. Underground engineering can be a part of effective design and solution of problems. Therefore, the underground is an important resource to enhance urban resilience, as is summarized in Table 1.

As we create and use more underground space, particularly in urban environments, we may find ourselves working in ground conditions not experienced before. This means that much of our conventional and current wisdom based on local experience may not be applicable. For example, we anticipate increased use of deeper underground space for many purposes. Higher ground stresses, temperatures and water volumes and pressures (often with poor quality) will likely be encountered, and soil and rock behavior may become more problematic (Fairhurst, 2017). Figure 2 contains data on the depth of shafts constructed in the U.S. over the past 150 years – clearly reflecting the trend of greater depth over time. As new needs for underground space are identified, owners and the public will request larger and more complex 3-D complex geometry for underground space applications. This may require advanced design concepts for long-term performance and stability. And as our coastal cities grow, more of the new infrastructure must be placed into more challenging ground for which risks and costs may be higher. This may require new approaches to ground improvement and displacement control.

Table 1. Advantages and Disadvantages for Underground Infrastructure and Extreme Event Impacts (modified from personal work of R. L. Sterling).

Type of Extreme Event	Advantages or mitigations	Disadvantages or limitations
Earthquake	Ground motions reduce rapidly below surface	Fault displacements must be accommodated
	Structures move with the ground	Instability in weak materials or poor lining backfill
Winds: hurricane, tornado	Minimal impact on fully buried structures	Damage to shallow utilities from toppling surface structures and trees
Water: Surge, flood, tsunami, sea level rise	Protection from direct impact, mass wasting and debris flows	Extensive restoration time and cost if entrances are flooded
Fire, blast, terrorism	Ground provides thermal and concussion protection, limit impact by compartmentalization	Entrances and exposed surfaces are weaknesses, confined space risk
External radiation, chemical/biological exposure	Ground provides additional protection	Appropriate ventilation system protections required

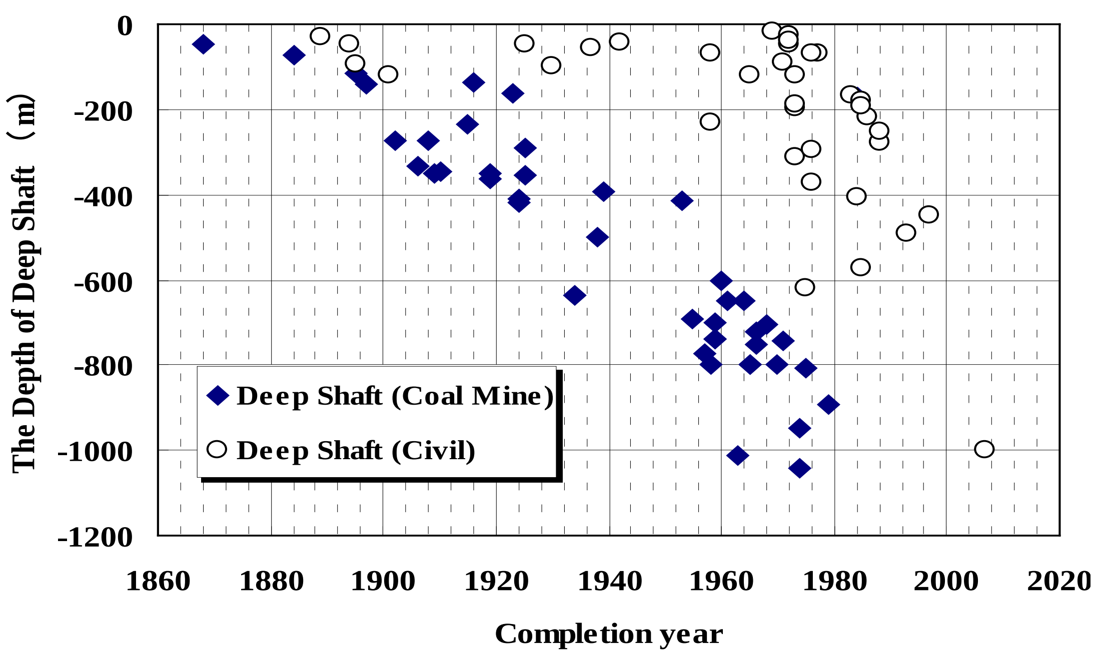

Figure 2. U.S. Data on Depths of Coal and Civil Deep Shafts 1860 – 2010

REDUCTION OF COSTS AND RISKS

Beyond the need for reliable and resilient infrastructure services, is the need to manage the budget. It is notable that infrastructure costs for construction and rehabilitation have generally and significantly increased in recent time. Innovations are needed to reduce costs and support schedule reliability, and best decisions on investments can only be made with increased use of Life Cycle Engineering (LCE) which requires data bases that by-and-large do not exist. With increased use of LCE, performance metrics can be established for integrated surface and underground infrastructure planning and design, and to support sustainable multi-hazard design and LCE trade-offs. For evaluation and surface vs underground placement trade-off studies, we need to know the value of underground space. However, there is no developed market that can establish an underground space value – what is the cost for 1 m^3 of underground space at 100 m depth in New York City? All this leads to a new profession of urban stewardship engineers who design and construct holistically.

It is also imperative that the physical facilities be made more durable, and the infrastructure performance be made more reliable. Cost increases are often driven by increased risks: Risk = Probability x Consequences (or Impact). For consequence evaluation, we need an improved quantitative evaluate risks, impacts and their probability of occurrence, as well as a framework for evaluation of mitigation strategy and assignment of responsibility during construction and in operation. For example, most current flood models in urban areas fail to consider subsurface spaces in characterizing the effects of flooding, and the impacts of sea-level rise on both construction and operation of our underground systems needs to be assessed. Overall, the urban engineer must have a commitment to maintain holistic stewardship of our cities, including: 1) spatial (x, y and z) urban planning; 2) acute awareness of temporal issues (first cost, sustainability); 3) agility in integrating across physical infrastructure sectors, and across physical, natural, social, and fiscal environments and risks; and 4) the gift of communication that provides realistic expectations on cost and schedule to owners and to the public.

A majority of the risk associated with underground infrastructure construction and performance is derived from the spatial variability and uncertainty associated with geologic conditions, including soil, rock and water. Six areas of focus are discussed below:

- Risk avoidance
- New technologies and methods
- Better subsurface characterization
- Better management of water
- Risk awareness, assessment and management
- Risk communication and willingness to accept and share risk

RISK AVOIDANCE

Geologic conditions in the subsurface should be primarily managed by invoking the concept of underground zoning which provides spatial thinking and integrated planning to place above- and below-ground facilities in an optimized geologic setting. In New York City and other cities, such a consideration leads to vertical segregation of different infrastructure systems. However, much of the shallow infrastructure represents spatial chaos and project costs are strongly impacted by the need to manage the mayhem of aged near-surface systems.

The Japanese experience is a bit different (Masuda et al., 2004). The 2001 Deep Underground Utilization Law established that land ownership rights in populated areas (e.g., Tokyo, Osaka) only extend to 40 meters below ground, or 10 m below a deep foundation (Li, 2013 and see Figure 3). The act is focused on metropolitan areas of Tokyo and Osaka, Nagoya, and ensures the right of certain developers to use deep underground space regardless of surface ownership. In the case of public use of the underground space, no compensation to the land owner is required. The first projects using the law have included underground water mains in Kobe, and the Tokyo Gaikan Expressway. In 2015 Singapore adopted a similar approach by limiting ownership to a specific depth (30m below Singapore Height Datum (SHD) (Stones and Heng, 2016).

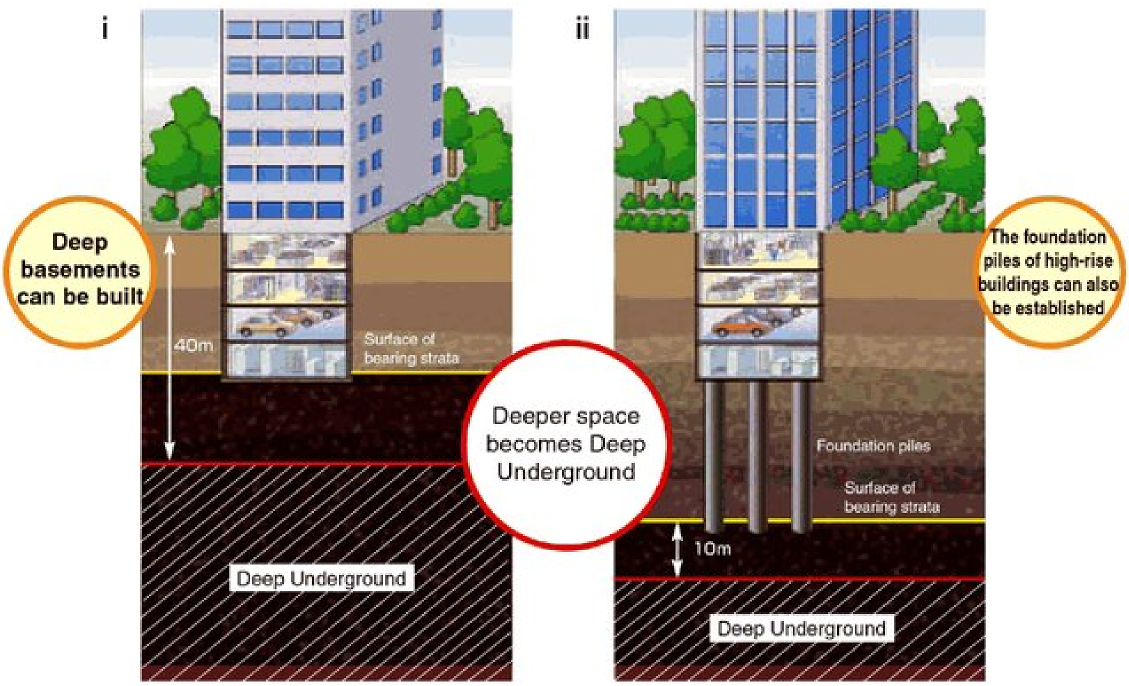

Figure 3. Schematic of Impacts of the 2001 Deep Underground Utilization Law in Japan (Li, 2013)

NEW TECHNOLOGIES AND METHODS

The underground industry has many methods that can be applied including Tunnel Boring Machines (TBMs) and shields, and the newer slurry, earth pressure balance and hybrid pressure-face equipment, but more developments are needed to decrease costs, and improve safety (e.g., avoid hyperbaric cutter replacements and other interventions). The seemingly inexorable trend is for larger and larger diameters, and this by itself drives up project costs and expands project schedule.

In many areas of research, the pipeline from fundamental research to application has been thwarted. It is imperative that industry and owners commit to partner with universities to develop new technologies and methods, including new ways to excavate and support underground openings. In addition, it is important to incentivize the application of new technologies. For example, ground improvement techniques have come a long way in the past 30 years, as is reflected by the data in Figure 4 for U.S road tunnel support over the period from 1980 to 2000. The transition from ribs-and-lagging to NATM methods is clear, and begs the issue that the long-term performance of newer method of construction need to be monitored in service so that expectations for support/lining life can be verified. It is important that advances continue, and that techniques of ground improvement be proactively implemented before a project is

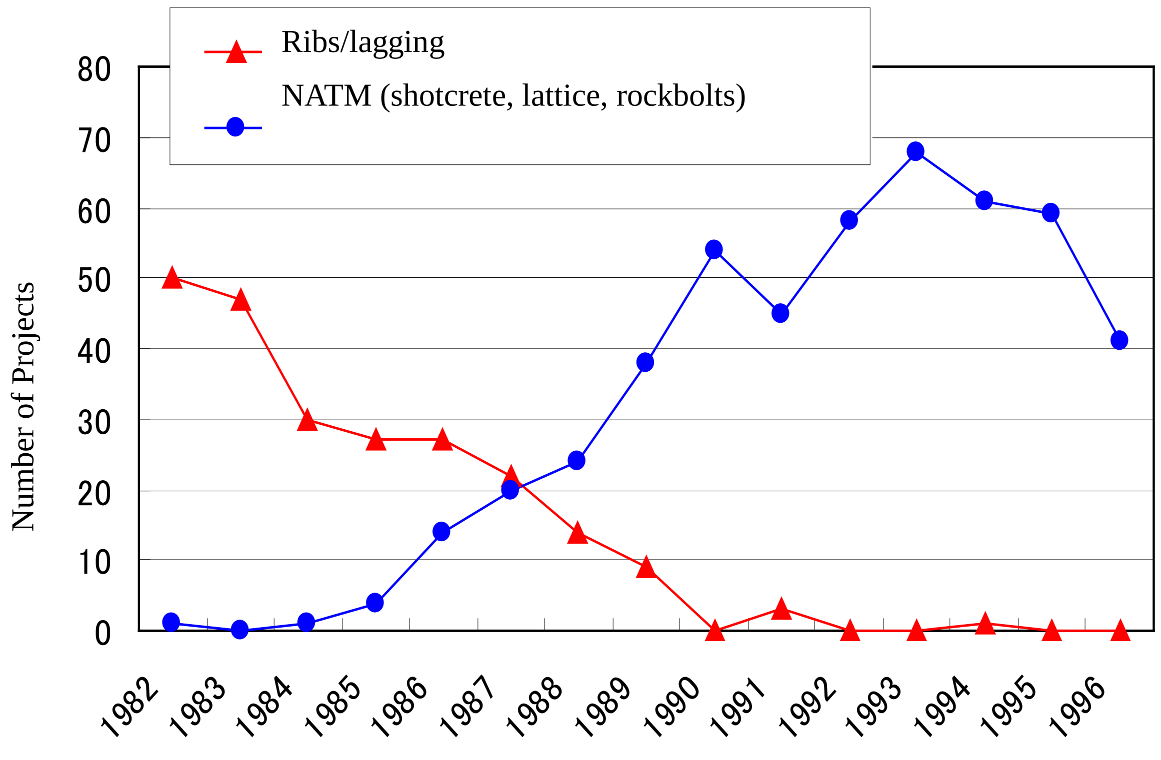

Figure 4 Data Documenting the Change in U.S. Road Tunnel Support Methods Between 1980 and 2000 (data from FHWA)

started to change and remove identified geologic risks, rather than respond to the risks as encountered. Such postures often result in changed condition claims, litigation, increased costs and delays.

Many of our infrastructure projects are designed for low first cost and to comply with right-of-way limitations. Such systems are not necessarily designed for long-term sustainability and maintainability. Engineers must seek new materials and technologies to enhance performance and durability of our infrastructure systems, new and old. In addition, new technologies must not be just implemented – they must be assessed for short and long-term performance. Sober assessment of performance is very often forgotten in the cycle of innovation we seek for the underground industries.

Safety in the underground during construction and operation continues as a concern, and incident rates for heavy construction are considerably higher than for mining projects. Safety innovations continue to be needed, and include personal protective equipment during construction and also fire and explosion incident management, particularly when the public are involved in response.

Spatial and temporal variations in subsurface materials and conditions continue to be a risk, and a new look at integrating geophysical and remote sensing methods is warranted. Engineers should also rethink materials and methods in use. For example, development of new concrete, grout and shotcrete materials for application in the underground are needed, and engineers and contractors should revisit and dramatically improve our "old" or "conventional" technologies such as drill/blast operations.

BETTER SUBSURFACE CHARACTERIZATION

Knowledge of the underground conditions has been improving over past decades, but the combination of continuing sore points and arising new difficulties must be considered in planning. In many urban environments, previous underground works have demonstrated spatial and material property distributions to be expected, so our conventional site investigations should be confirmatory rather than exploratory.

But some geologic issues continue without full resolutions, as a low-grade infection on the industry. Examples include the following:

- Shallow cover, varying depth to rock
- Ground movements, subsidence
- Consolidation settlements
- Weathered rock and rock mass (including karst)
- Rock mass structure and variability
- Time dependency in materials behavior
- Muck abrasiveness and stickiness
- Aggregate reactions and concrete durability

Geological and Geotechnical Engineers still wrestle with scale effects as well, extrapolating from lab behavior to full scale in the field. Many rock mass rating systems have been developed. On a large number of projects, ratings applications have been uninformed and inconsistent, and there have been only limited attempts to validate their inference, or the use of a large number of empirical correlations. This observation also can be applied to the plethora of computational models available for subsurface design. We must make opportunities to validate design assumptions and performance prediction.

More urban infrastructure will necessarily be placed deeper, and the in situ stress state will likely become more important on more projects. Estimation of an in situ stress field is challenging without a clear geologic framework for interpretation, and most stress assessments are made as point measurements (interpretation of deformation measurements at a point). This can only be addressed by obtaining a better understanding of the spatial variability of rock mass structured which introduces uncertainty. The variety of excavation shapes and dimensions can be expected to vary in the future, with more gallery space rather than plane strain tunnels needed, making the predictions of displacements, strains and stress redistribution around an underground opening increasingly important. We also need to understand spatial and temporal variations that affect performance of existing facilities for sustainable design and operations.

Geologic material failure and time-dependent response of geologic materials are far more likely to be observed in an underground mine than in a civil works project. Mining engineers develop a strong geologic perspective on risk that would benefit in application to civil construction projects. Such a partnership or collaboration across industries brings an enhanced potential for real spatial understanding of rock mass and water inflow and pressures variability, and for better understanding of time effects, presenting the possibility to develop sustainability performance information. The two industries also have many environmental issues in common, as do they have a mutually beneficial potential for application of automation, robotics, and big data/information systems. This is the era of information: with an expansion in sensing and measurement capabilities, how should the entire site investigation and construction process be re-thought, not to mention real-time data flows and their importance to effective management for resilience of urban infrastructure systems.

BETTER MANAGEMENT OF WATER

The presence of water in the subsurface changes the behavior of materials, and strongly influences the long-term performance of underground facilities. Full consideration of the influence of water includes knowledge and understanding of volume, flow rate, quality, pressure, and changes over time. On many tunnel projects, water is encountered but few of these parameters are assessed or evaluated for spatial variability unless a claim is anticipated. Such observations and measurements are required if we are to significantly reduce the impact of water. Research is also needed on the relationship between fracture mechanical aperture and hydraulic aperture with consideration for rock type and geologic regime, diagenesis, discontinuity fillings, normal stress and shear stress along and across fractures (Chen, 2010).

Management of water is sometimes a matter of resource conservation (e.g., impacts on a water supply), but environmental (bio-geochemical) and construction impacts are likely to be more common and profound. During construction, water management includes compressed air, grouting, and the use of pressure-faced shields. Microtunneling and trenchless methods are very flexible and work well for smaller diameter emplacements, which can be efficiently and economically reamed to larger diameters – potentially minimizing the impact of water inflows on construction. Water inflows can compromise worker safety, and in some cases may compromise the capabilities of installed support.

Some of the most active areas of new technology implementation have been related to the introduction of waterproofing into tunnel linings. The long-term performance of such installations needs to be assessed on a continuing basis. Operational impacts of seepage and inflows are incredibly important since water drives long term deterioration in the underground, and inflows can cause piping and ground loss that affects lining performance and also structures nearby. The long-term performance of waterproofing or drainage management technologies is not well documented.

RISK AWARENESS, ASSESSMENT AND MANAGEMENT

Many underground construction projects now use the three-legged stool of a Disputes Review Board (DRB) requirement for bid documents to be escrowed, and the development of a Geotechnical Baseline Report (GBR) as a part of the contract documents explicitly developed for geologic risk management. A good GBR is thoughtfully written to present a geologic analysis of expected conditions, and or "geoproblem event" frequency (temporally and spatially) to be assumed during a project. The project data collected informs designers and contractors as to behaviors and properties of geologic materials, but a statistical assessment of the probability and consequences of encountering major geotechnically-driven stoppages in underground excavations is difficult – and yet such events are the main causes of major problems on underground construction projects.

The industry as a whole should commit to building a geologically-framed data base that includes spatial information about soil and rock mass variability and impacts in a geologic context. Such a data resource can inform regarding likelihood of problems being encountered and how, for different construction means and methods, the problem conditions may be best managed. The data and information needed include:

- Type of geoproblem event
- Means and methods of excavation and equipment
- Ground and water control

- Spatial frequency: length of each encountered problem, and distance between events
- Temporal frequency: hours to handle, and time between events
- Agility and performance of the contractor in responding to each geoproblem event

Not everything encountered on a specific project needs to be considered as a "one-off", and the framework of geologic inference and analysis opens the prospect for real predictability of geotechnical event with extreme impact on a project. For this geologic effort, it is clear that the mining and civil industries can share geodata.

RISK COMMUNICATION AND WILLINGNESS TO ACCEPT AND SHARE RISK

The commitment for investment requires far more effective communication of the value of infrastructure and of underground space. The value of the nation's infrastructure may be estimated in several ways, but totals on the order of $70 to $100 trillion can be suggested for the U.S. If this number is divided by the population of the US, the per capita investment in infrastructure is on the order of $300,000, the price of a house in many areas. This $300K can be interpreted as a birthright for each person born in the U.S., a pre-investment upon which the economic engine runs, the quality of life is assured, and career potential of each individual is leveraged. Even as families reinvest in a house to retain value, so must the nation reinvest in its infrastructure. This is an example of a metric that can be meaningful to each citizen and politician.

BUILDING A FRAMEWORK MODEL OF GEOLOGIC SPATIAL VARIABILITY FOR ANTICIPATION AND MANAGEMENT OF GEOLOGIC RISK IN THE UNDERGROUND

Design in the underground is best accomplished by anticipating materials, behavior and properties needed for intelligent analysis and construction in the underground. The greatest risk for most underground project success is derived from lack of geologic knowledge, including uncertainty about groundwater, and about spatial material and property distributions. The greatest risk for long-term performance is uncertainty about as-built construction, and uncertainty concerning time-dependent behavior. What is warranted is a "Grand Campaign" to provide the knowledge base to address these risks.

Underground construction and tunnel engineers should graduate from curricula that include much more training in geology. Such training (especially field training and experience for students and professors) is mandatory for the geotechnical engineering profession to address geologic uncertainty by enhancing knowledge and application of the fundamentals of geologic knowledge and interpretation. Many geologic issues continue to be encountered and have problematic impacts like a thorn in the side, such as shallow cover and weathered rock, progressive deterioration, piping, and caving. Ground loss consequences include construction settlement, subsidence, impact on structures, consolidation with water table changes, and differential settlement associated with a varying depth to top of rock. These are perhaps the “low-grade infections” in comparison to the “high fever” of geoproblems that cause extensive stoppages. In addition, there is a growing overreliance on (and misuse of) rock mass ratings - RQD on steroids.

We should be systematically accessing any and all surface and underground exposures of geologic materials, and acquire 3D and temporal information about the spatial distribution of material characteristics in different geologic regimes of formation and stress history. This includes field work at exposures such as road cuts and natural exposures, underground excavations, and mined openings. This work also includes recording and assessment of encountered and managed risk on real projects involving surface and underground excavations. The outcome from such an effort will be development of a rational and guided geologically-informed framework for engineers, designers and contractors to characterize geologic variability and uncertainty in a form that can be applied to project management and execution, and management of risks.

SUMMARY AND CONCLUSIONS

Engineers must partner with geologists, architects, and planners in new designs for urban underground space in the future, and such space will be much more than tunnels and stations. These professions must collaborate and prepare for the creative use of urban underground space that our society will demand in terms of excavated shapes/depths, human occupancy (social acceptance of underground space, spatial referencing, emergency response, aging population). These professions must support the development and deployment of new technologies that will serve the requirements for flexibility and quality of facilities in our finite urban spatial resources.

While geologic uncertainties and impacts are the focus here, engineers should fundamentally rethink materials and methods, including development and application of advanced methods for subsurface characterization and to extend applications for ground improvement methods. The framework for understanding risk and spatial variability of geologic conditions should be improved, and should our proficiency and understanding of assessment and redistribution of in situ stress. Improvements are also needed in excavation methods including drill/blast, lasers and other innovative technologies methods.

For engineers, professional homework is required. Data to support rational and long-term sustainable design and LCE need to be acquired, including time-dependency. In addition, the true value of underground space needs to be determined, effectively by creating a market that can establish a value for, say, a cubic meter of underground space in certain soil or rock conditions.

With underground and geologic conditions managed more effectively, we will be in a position to support development of a new understanding and acceptance of urban underground design for the public.

ACKNOWLEDGEMENTS

Appreciation is given to financial support provided by many funding agencies over the past 40 years. The opinions expressed in this paper are those of the author and not that the funding agencies.

REFERENCES

American Society of Civil Engineers. 2017. Report Card for America's Infrastructure, http://www.infrastructurereportcard.org/.

Anex, Robert. P., Realff, Matthew. J., and Wallace, William. A. 2006. Resilient and Sustainable Infrastructure Networks (RESIN). NSF Workshop Report, http://www3.abe.iastate.edu/biobased/RESIN.htm.

AWWA. 2001. Reinvesting in Drinking Water Infrastructure, AWWA Water Industry Technical Action Fund, http://www.mcwane.com/upl/downloads/resources/americas-water-infrastructure-challenge/reinvesting-in-drinking-water-infrastructure.pdf.

Bobylev, N. 2009. Urban underground infrastructure and climate change: opportunities and threats. *Proc. 5th Urban Research Symposium*, Marseille, France, http://www.urs2009.net/docs/papers/Bobylev.pdf.

Bobylev, N. 2016. Underground Space as an urban indicator: Measuring use of subsurface. *Tunnelling and Underground Space Technology*. Vol 55, DOI: 10.1016/j.tust.2015.10.024 · License: CC BY-NC-ND 4.0

Chen, R. 2010. Groundwater Inflow into Rock Tunnels. Doctoral Dissertation, University of Texas at Austin. https://repositories.lib.utexas.edu/bitstream/handle/2152/ETD-UT-2010-08-1677/CHEN-DISSERTATION.pdf

Fairhurst, C. 2017. Some Challenges of Deep Mining. *Engineering*. Vol. 3, Issue 4, pp. 527-537.

Hoeppe, P. 2016. Trends in weather related disasters – Consequences for insurers and society. *Weather and Extreme Climates*. Vol. 11, pp. 70-79.

Li, H. 2013. An integrated strategy for sustainable development of the urban underground: From strategic, economic and societal aspects. Thesis No. 5869. École Polytechnique Federale de Lausanne.

https://www.researchgate.net/publication/283489860_An_Integrated_Strategy_for_Sustainable_Underground_Urbanization

Masuda, Y., N. Takahashi and T. Ojima. 2004. Utilization of Deep Underground Space in Tokyo – Urban Renewal with the City's New Backbone Lifeline. *Proc. Council on all Buildings and Urban Habitat*. Seoul. http://global.ctbuh.org/resources/papers/download/1590-utilization-of-deep-underground-space-in-tokyo-urban-renewal-with-the-citys-new-backbone-lifeline.pdf

Nelson, P. P. and R. Sterling, R. 2012. Sustainability and Resilience of Underground Urban Infrastructure: New Approaches to Metrics and Formalism, *ASCE GSP*, 10 pp.

Nelson, P. P. 2016. A Framework for the Future of Underground Urban Engineering. *Tunnelling and Underground Space Technology*. Vol. 55, pp. 32-39.

Nelson, P. P. and H. S. Düzgün. 2018. Resilience Impacts from Integrated Above- and Below-ground Urban Infrastructure. *Proc. World Tunnelling Congress*, Dubai, UAE.

Sherrieb, K., Norris, F. H., and Galea, S. 2010. Measuring Capacities for Community Resilience. *Social Indicators Research*, Vol. 99 (2), pp. 227-247.

Stones, P. and T. Y. Heng. 2016. Underground Space Development Key Planning Factors. *Procedia Engineering*, 165, pp. 343-354.